5 IMPLEMENTATION OF DISPOSITION SURVEYS

5.1 Introduction

This chapter discusses the implementation phase of the Data Life Cycle and focuses on controlling measurement uncertainty. The information in this chapter describes approaches for safely implementing the final disposition survey design developed in Chapter 4, methods for controlling uncertainty, and techniques to determine whether the measurement results achieve the survey objectives.

Similar to MARSSIM, MARSAME excludes specific recommendations for implementing disposition surveys. Instead, MARSAME provides generic recommendations and information to assist the user in selecting measurement techniques for implementing the survey design. This approach encourages consideration of innovative measurement techniques and emphasizes the flexibility of the information in MARSAME.

Implementation begins with health and safety considerations for the disposition survey (Section 5.2). Section 5.3 provides information on handling M&E, while Section 5.4 discusses segregating M&E based on physical and radiological attributes. Section 5.5 continues the discussion of measurement quality objectives (MQOs) from Chapters 3 and 4. Measurement uncertainty (Section 5.6), detectability (Section 5.7), and quantifiability (Section 5.8), are three MQOs that are described in greater detail. Combining an instrument with a measurement technique to ensure the MQOs are achieved is discussed in Section 5.9. Section 5.10 provides information on quality control (QC), and information on data reporting is provided in Section 5.11.

5.2 Ensure Protection of Health and Safety

Health and safety is emphasized as an issue potentially affecting the implementation of MARSAME disposition surveys. The focus of minimizing hazards is shifted away from environmental hazards (e.g., confined spaces, unstable surfaces, heat and cold stress) and tailored towards scenarios where health and safety issues may affect how a disposition survey is designed and performed. Work areas and procedures that present potential safety hazards must be identified and evaluated to warn personnel of potential hazards. Personnel must be trained with regards to potential physical and chemical safety hazards (e.g., inhalation, adsorption, ingestion, and injection/puncturing) and the potential for injury (slips, trips, falls, burns, etc.).

A job safety analysis (JSA) should be performed prior to implementing a disposition survey. The JSA offers an organized approach to the task of locating problem areas for material handling safety (OSHA 2002). The JSA should be used to identify hazards and provide inputs for drafting a health and safety plan (HASP). The HASP will address the potential hazards associated with M&E handling and movement and should be prepared concurrently with the survey design. The HASP identifies methods to minimize the threats posed by the potential hazards. The information in the HASP may influence the selection of a measurement technique and disposition survey procedures. Radiation work permits (RWPs) may be established to control access to radiologically controlled areas. RWPs contain requirements from the JSA such as dosimetry and personal protective equipment (PPE), as well as survey maps illustrating predicted dose rates and related radiological concerns (e.g., removable or airborne radioactivity). Hazard work permits (HWPs) may be used in place of RWPs at sites with primarily physical or chemical hazards. The Case Study presented in Chapter 7 (see Section 7.3.6.1) provides an example of a JSA.

The JSA systematically carries out the basic strategy of accident prevention through the recognition, evaluation, and control of hazards associated with a given job as well as the determination of the safest, most efficient method of performing that job. This process creates a framework for deciding between engineering controls, administrative controls, and PPE for the purpose of controlling or correcting unsafe conditions (Hatch 1978). Examples of these controls include:

- Engineering controls – physical changes in processes or machinery (e.g., installing guards to restrict access to moving parts during operation), storage configuration (e.g., using shelves in place of piles or stacks).

- Administrative controls – changes in work practices and organization (e.g., restricted areas where it is not safe to eat, drink, smoke, etc.) including the placement of signs to warn personnel of hazards.

- Personal protective equipment (PPE) – clothing or devices worn by employees to protect against hazards (e.g., gloves, respirator, full-body suits, etc.).

Correction measures may incorporate principles of all of the controls listed above. The preferred method of control is through engineering controls, followed by administrative controls, and then personal protective equipment.

Proper handling procedures for hazardous M&E are documented in site-specific health and safety plans. Compliance with all control requirements is mandatory to maintain a safe working environment. Personnel must regard control requirements as a framework to facilitate health and safety, while still taking responsibility for their own well being. Being wary of safety hazards remains an individual responsibility, and personnel must be aware of their surroundings at all times in work areas.

5.3 Consider Issues for Handling M&E

Materials and equipment handling is addressed in this document as a process control issue. M&E handling requirements are determined by the final integrated survey design (see Section 4.4) and the combination of instrumentation and measurement technique used to perform the survey (see Section 5.9). M&E may also require handling to more closely match the assumptions used to develop instrument calibrations used to determine measurement uncertainty (see Section 5.6), measurement detectability (see Section 5.7), and measurement quantifiability (see Section 5.8).

Typically, M&E will be handled to:

- Prepare a measurement grid or arrange M&E to perform a survey.
- Provide access for performing measurements.
- Transport the M&E to a different location.

5.3.1 Prepare M&E for Survey

Depending on the survey design, or assumptions used to develop the survey design, it may be necessary to prepare the M&E for survey. The amount of preparation required is determined by the DQOs and MQOs, and ranges from identifying measurement locations to adjusting the physical characteristics of the M&E (e.g., disassembly, segregation, physical arrangement).

The performance of a MARSSIM-type survey requires determining the location where the measurements are to be performed. The DQOs will determine the level of effort required to identify, mark, and record measurement locations.

Identifying measurement locations can be problematic because MARSSIM-type surveys recommend samples to be located either randomly (Class 3) or on a systematic grid (Class 1 and Class 2). Class 2 and Class 3 scan-only and in situ surveys do not require 100% of the M&E to be measured, so a method of identifying which portions will be measured is required.

Bulk materials or M&E consisting of many small, regularly shaped objects can be spread out in a uniform layer, and a two-dimensional grid can be superimposed on the surface to identify measurement locations. However, it is virtually impossible to identify random or systematic locations on M&E that consist of relatively few, large, irregularly shaped objects. The reason is that it is virtually impossible to establish a reference grid for these M&E. It is important to note that the objective for random locations is to allow every portion of the survey unit the same opportunity to be measured. Alternatively, the objective of systematic locations is to distribute the measurement locations equally. It is only necessary to establish a reference grid to sufficiently identify the measurement locations to meet the survey objectives.

One way to approximate a reference grid for locating measurements is to establish a grid in the area where the survey will be performed. The M&E to be surveyed are laid out in a single layer within the grid. The grid can then be used to identify measurement locations. Another option for locating measurements involves superimposing a grid on top of the M&E. A net could be laid over the M&E to be surveyed, ropes could be laid over the M&E to form a grid, or lights on a grid could be directed onto the M&E to approximate a grid and identify measurement locations.

If measurement locations cannot be identified with a grid, there may be no alternative but to perform biased measurements. Measurements would be preferentially performed in locations more likely to contain radionuclides or radioactivity, based on the results of the IA (see Section 2.5). This process involves professional judgment and may result in overestimating the average radionuclide concentration or level of radioactivity. In all cases, it is important to document the criteria used for identifying measurement locations and to document that these criteria were followed.

Marking measurement locations, once they have been identified, should be done in a way that will not interfere with the measurement. For example, using paint to mark the location of an alpha measurement could end up masking the presence of alpha activity. Using arrows, marking borders, or using an alternate method for marking locations (e.g., encircling with chalk) should be considered for these types of situations.

Recording measurement locations may be required as part of the survey objectives if the measurements may need to be repeated. For example, a large piece of equipment is surveyed prior to use on a decommissioning or cleanup project. If the exact same locations will be surveyed at the completion of the project, it will be necessary to record the measurement locations. Permanent or semi-permanent markings can be used to identify the measurement locations. Video or photographic records of measurement locations can also be used to return to a specific measurement location.

5.3.2 Provide Access

Large pieces of equipment may require special handling considerations. Large, mobile equipment (e.g., front loader, bulldozer, or crane) typically requires a specially trained operator. The operator may need to be available during the disposition survey to provide access to all areas requiring survey (e.g., move the equipment to provide access to the bottom of tires or treads). Other large items may require special equipment (e.g., a crane or lift) to provide access to all areas requiring survey. Special health and safety issues (Section 5.2) may be required to ensure protection of survey personnel from physical hazards (e.g., personnel or items falling from heights, or large items dropping on personnel or equipment). It may be necessary to partially or totally disassemble large pieces of equipment to provide access and ensure measurability.

Piles of M&E may involve special handling precautions. Piles of dispersible M&E (e.g., soil or concrete rubble) may need to be rearranged to match the assumptions used to develop the instrument efficiency. For example, a conical pile of soil may need to be flattened to a uniform thickness to ensure measurability. If the M&E consists of or contains a significant amount of dust, precautions against generating an airborne radiation hazard may be necessary. Since many dust control systems use liquids to prevent the dust from becoming airborne, it may be necessary to account for dust control impacts on measurability of the M&E. For example, adding water to control dust will make it more difficult to measure alpha radioactivity. Piles of scrap may also present other health and safety concerns along with issues related to measurability. Sharp edges, pinch points, and unstable piles are examples of handling problems that may need to be addressed.

Small pieces of M&E may be surveyed individually or combined into groups for survey. Care should be taken when combining items to prevent mixing impacted and non-impacted items, or mixing items with different physical or radiological attributes (see Section 2.2 and Section 5.4).

The moving of materials at a given site may require labeling as a quality control measure to ensure M&E movement is tracked and documented. Labeling will help avoid the commingling of impacted and non-impacted materials, and facilitate the staging and storage of impacted and non-impacted M&E in appropriate areas.

5.3.3 Transport the M&E

Identification of impacted and non-impacted areas within a facility will assist in selecting areas for storing, staging, and surveying impacted M&E. In general, impacted M&E should be stored, staged, and surveyed in impacted areas. Care should be taken when moving or handling impacted M&E to prevent the spread of radionuclides to non-impacted areas. M&E in areas with airborne radioactivity issues should be moved to protect the personnel conducting surveys and reduce the possibility of contaminating survey instruments.

Disposition surveys can be performed with the M&E in place, or the M&E can be moved to another location. For example, work areas with high levels of radioactivity may make it difficult or resource intensive to meet the MQOs for measurement detectability (Section 5.7) or quantifiability (Section 5.8). Moving the M&E to areas with lower levels of radioactivity will help reduce radiation exposure for personnel conducting surveys and facilitate meeting the survey objectives.

5.4 Segregate the M&E

The purpose of segregation is to separate M&E based on the estimated total measurement uncertainty, ease of handling, and disposition options. Segregation is based on the physical and radiological attributes determined during the Initial Assessment (IA, see Chapter 2), not only on radionuclide concentrations or radiation levels (i.e., classification).

In general, segregation based on measurement uncertainty should consider the physical and radiological attributes that affect efficiency (i.e., geometry and fluence rate). M&E with simple geometries, such as drums (cylinder) and flat surfaces (plane), should be separated from M&E with complex geometries. Fluence rate is affected by location of the radioactivity (i.e., surficial or volumetric) as well as surface effects (e.g., rough or smooth), density of the M&E, and type and energy of radiation. High fluence rates are associated with surface radioactivity with high energy on flat smooth surfaces made from materials with high atomic number (due to increased backscatter). Volumetric activity, shielded surfaces, alpha or low energy or beta radiations, irregular shapes, or rough surfaces can cause lower fluence rates. All of these factors should be considered when segregating M&E.

Segregation of M&E should be performed conservatively. This means that the user should separate M&E when they are not obviously similar. It is always possible to combine M&E but it is not always practical or possible, to separate M&E once they have been combined. For example, consider a facility where all the waste materials (e.g., paper, wood, metal, broken equipment) are combined into a single "trash pile." When the planning team considers different measurement methods and disposition options, they identify an innovative measurement method that only applies to non-ferrous scrap metal. This would allow for recycling of these materials with significant cost recovery as opposed to disposal. If the cost of re-segregating the M&E is not offset by the value of recycling these materials, it may not be practical to segregate the non-ferrous metals.

It is important to note that segregation does not require physical separation. Consider a generic large box geometry, such as an empty shipping container or railroad car. The large, flat sides could be considered separate survey units from the corners. Therefore, separate surveys would be designed for the corners and the sides even though the entire railroad car would remain intact throughout implementation of the disposition survey. Alternatively (or additionally), obvious flaws, corrosion areas, or damaged areas could be segregated from the areas in good condition. Even if the entire object is eventually surveyed using a single in situ measurement (e.g., in situ gamma spectrometry) it is important to segregate the M&E (at least conceptually) so an adequate evaluation of alternate measurement methods can be performed (see Section 5.9).

Handling of M&E during disposition surveys should also be considered during segregation (see Section 5.3). Physical characteristics of the M&E should be considered when segregating based on handling requirements. Small, light items are easier to move and gain access to all surfaces than large, massive items. M&E that will require preparation (e.g., disassembly, crushing, chopping) prior to survey should be segregated from M&E that can be surveyed in their present form. Disposition options should also be considered when segregating M&E. M&E that can be reused or recycled should be segregated from M&E that is being considered for disposal. Selection of disposition options was discussed in Section 2.4.

5.5 Set Measurement Quality Objectives

A number of terms with specific statistical meanings are used in this and subsequent sections. These terms are defined in Appendix G. The concept of Measurement Quality Objectives (MQOs) and in particular the required measurement method uncertainty was introduced in Section 3.8. These ideas are discussed in greater detail in the Multi-Agency Radiological Laboratory Analytical Protocols Manual (MARLAP 2004) Chapter 3 and Appendix C. While MARLAP is focused on radioanalytical procedures, these concepts are applicable on a much broader scale and will be used in MARSAME to guide the selection of measurement methods for disposition surveys for materials and equipment.

Section 4.2 discussed the DQO process for developing statistical hypothesis tests for the implementation of disposition decision rules using measurement data. This included formulating the null and alternative hypotheses, defining the gray region using the action level and discrimination limit, and setting the desired limits on potential Type I and Type II decision error probabilities that a decision maker is willing to accept for project results. Decision errors are possible, at least in part, because measurement results have uncertainties. The effect of these uncertainties is expressed in the size of the relative shift, Δ/σ, introduced in Section 4.2.2. The overall uncertainty, σ, has components that may be due to spatial variability in radioactivity concentration, σ_S, but also because of uncertainty in the measurement method σ_M. Because DQOs apply to both sampling and measurement activities, what are needed from a measurement perspective are method performance characteristics specifically for the measurement process of a particular project. These method performance characteristics (see Section 3.8) are the measurement quality objectives (MQOs).

DQOs define the performance criteria that limit the probabilities of making decision errors by:

- Considering the purpose of collecting the data
- Defining the appropriate type of data needed
- Specifying tolerable probabilities of making decision errors

DQOs apply to both sampling and measurement activities.

MQOs can be viewed as the measurement portion of the overall project DQOs (see Section 3.8). MQOs are:

- the part of the project DQOs that apply to the measured result and its associated uncertainty.
- statements of measurement performance objectives or requirements for a particular measurement method performance characteristic, for example, measurement method uncertainty and detection capability.
- used initially for the selection and evaluation of measurement methods.
- are subsequently used for the ongoing and final evaluation of the measurement data.

Measurement method uncertainty refers to the <u>predicted</u> uncertainty of a measured value that would be calculated if the method were applied to a hypothetical sample with a specified concentration. Measurement method uncertainty is a characteristic of the measurement method and the measurement process. Measurement uncertainty, as opposed to spatial uncertainty, is a characteristic of an individual measurement.

The true measurement method standard deviation, σ_M, is a theoretical quantity and is never known exactly, but it may be estimated using the methods described in Section 5.6. The estimate of σ_M will be denoted here by u_M and called the "measurement method uncertainty." The measurement method uncertainty, when estimated by uncertainty propagation, is the predicted value of the combined standard uncertainty ("one-sigma" uncertainty) of the measurement for material with concentration equal to the UBGR. Note that the term "measurement method uncertainty" and the symbol u_M actually apply not just to the measurement method but also to the entire measurement process, that is, it should include uncertainties in how the measurement method is actually implemented.

The true standard deviation of the measurement method, σ_M, is unknown but σ_{MR}, is intended to be an upper bound for σ_M. In practice, σ_{MR} is actually used as an upper bound for the method uncertainty, u_M, which is an estimate of σ_M. Therefore, the value of σ_{MR} will be called the "required measurement method uncertainty" and denoted by u_{MR}.

The principal MQOs in any project will be defined by the required measurement method uncertainty, u_{MR}, at and below the UBGR and the relative required measurement method uncertainty, φ_{MR}, at and above the UBGR, $\varphi_{MR} = u_{MR}$ /UBGR. See Section 5.5.2 for further discussion.

When making decisions about individual measurement results u_{MR} should ideally be 0.3Δ, and when making decisions about the mean of several measurement results u_{MR} should ideally be 0.1Δ, where Δ is the width of the gray region, Δ = UBGR – LBGR. In developing these results, a number of new and sometimes only subtly different definitions and symbols are used. For the convenience of the reader, many of these are summarized in the tables in Appendix G.1.

5.5.1 Determine the Required Measurement Method Uncertainty at the UBGR

This section provides the rationale and guidance for establishing project-specific MQOs for controlling σ_M. This control is achieved by establishing a desired maximum measurement method uncertainty at the upper boundary of the gray region. This control also will assist in both the measurement method selection process and in the evaluation of measurement data. Approaches applicable to several situations are detailed below.

Three basic survey designs were described in Chapter 4: scan-only, in situ, and MARSSIM-type. The relative shift, Δ/σ, is important in determining the level of survey effort required in all three designs. For a given width of the gray region, Δ, the relative shift, Δ/σ, can only be controlled by controlling σ. The standard deviation, σ, may have both a measurement component, σ_M, and a sampling component, σ_S. Segregation and classification may help in controlling σ_S (see Sections 4.3 and 5.4).

For 100% scan-only surveys, the decision uncertainty associated with σ_S is essentially eliminated because the entire survey unit is measured. In class 2 survey units, the scan coverage can vary from 10% to nearly 100% depending on the value of Δ/σ. This is a reflection of the fact that for a fixed measurement variability, σ_M, smaller values of Δ/σ imply larger spatial variability. Larger spatial variability demands higher scan coverage to reduce the decision uncertainty. That is, more of the survey unit must be measured to lower the standard deviation of the mean. In such cases, it will be desirable to reduce σ_M until it is negligible in comparison to σ_S. σ_M can be considered negligible if it is no greater than $\sigma_S/3$. Therefore, MARSAME recommends the requirement $u_{MR} \leq \sigma_S/3$.

For in situ survey designs, either the entire survey unit, or a large portion of it, is covered with a single measurement. Thus, spatial variability will tend to be averaged out. When decisions are to be made by comparing such single measurements to an action level, the total variance of the data equals the measurement variance, σ_M^2, and the data distribution in most instances should be approximately normal. In these cases the DQOs will be met if

$$u_{MR} \leq \frac{\text{UBGR-LBGR}}{z_{1-\alpha} + z_{1-\beta}} = \frac{\Delta}{z_{1-\alpha} + z_{1-\beta}}$$

where $z_{1-\alpha}$, is the $(1-\alpha)$-quantile of the standard normal distribution and $z_{1-\beta}$, is the $(1-\beta)$-quantile of the standard normal distribution.

If $\alpha = \beta = 0.05$, then

$$u_{Mr} \leq \frac{\Delta}{z_{0.95} + z_{0.95}} = \frac{\Delta}{1.645 + 1.645} = \frac{\Delta}{3.29} \sim 0.3\,\Delta$$

Therefore, MARSAME recommends the requirement $u_{MR} \leq 0.3\Delta$. The details are discussed in Appendix G.1.2.

For the special case where the LBGR = 0, then Δ = UBGR and $\sigma_{MR} = \Delta / (z_{1-\alpha} + z_{1-\beta})$ implies

$$u_{MR} \leq \frac{UBGR}{z_{0.95} + z_{0.95}} = \frac{UBGR}{1.645 + 1.645} = \frac{UBGR}{3.29} \sim 0.3\,UBGR\,.$$

This is equivalent to requiring that the MDC (see Appendix G.3.2) be less than the action level. The MDC is defined as the concentration at which the probability of detection is $1 - \beta$ and the probability of false detection in a sample with zero concentration is at most α.

Example 1: Suppose the action level is 10,000 Bq/m^2 and the lower bound of the gray region is 5,000 Bq/m^2, $\alpha = 0.05$, and $\beta = 0.10$. If decisions are to be made about individual items, then the required measurement method uncertainty at 10,000 Bq/m^2 is

$$u_{MR} = \frac{\Delta}{z_{1-\alpha} + z_{1-\beta}} = \frac{10{,}000 \text{ Bq/m}^2 \text{-} 5{,}000 \text{ Bq/m}^2}{z_{0.95} + z_{0.90}} = \frac{5{,}000 \text{ Bq/m}^2}{1.645 + 1.282} = 1{,}700 \text{ Bq/m}^2$$

When a decision is to be made about the mean of a sampled population, generally the average of a set of measurements on a survey unit is compared to the disposition criterion. For MARSSIM-type designs, the ratio Δ/σ, called the "relative shift," determines the number of measurements required to achieve the desired decision error rates α and β. The target range for this ratio should be between 1 and 3, as explained in MARSSIM (MARSSIM 2002) and NUREG-1505 (NRC 1998a). Ideally, to keep the required number of measurements low, the DQOs are aimed at establishing $\Delta/\sigma \approx 3$. The cost in number of measurements rises rapidly as the ratio Δ/σ falls below 1, but there is little benefit from increasing the ratio much above 3. One of the main objectives in optimizing survey design is to achieve a relative shift, Δ/σ, of at least one and ideally three. Values of Δ/σ greater than three, while desirable, should not be pursued at additional cost. If Δ/σ is 3 and σ_M is negligible in comparison to σ_S, then σ_M will be $\Delta/10$. The details are discussed in Appendix G.1.1.

Therefore, MARSAME recommends the requirement $u_{MR} \leq \Delta / 10$ by default when decisions are being made about the mean of a sampled population. If the LBGR is zero, this is equivalent to requiring that the MQC be less than the action level (see Appendix G.1.1).

Example 2: Suppose the action level is 10,000 Bq/m^2 and the lower bound of the gray region is 2,000 Bq/m^2. If decisions are to be made about survey units based on measurements at several locations, then the required measurement method uncertainty (u_{MR}) at 10,000 Bq/m^2 is

$$\frac{\Delta}{10} = \frac{10,000 - 2,000}{10} = 800 \text{ Bq/m}^2$$

Example 3: Suppose the action level is 10,000 Bq/m^2, but this time assume the lower bound of the gray region is 0 Bq/m^2. In this case the required method measurement uncertainty, u_{MR}, at 10,000 Bq/m^2 is

$$u_{MR} = \frac{\Delta}{10} = (10{,}000 \text{ - } 0)/10 \;=\; 1{,}000 \text{ Bq/m}^2$$

The recommended values of u_{MR} are based on the assumption that any known bias in the measurement process has been corrected and that any remaining bias is well less than 10% of the shift, Δ, when a concentration near the gray region is measured.

Achieving a required measurement method uncertainty u_{MR} less than the recommended limits may be difficult in some situations. When the recommended requirement for u_{MR} is too difficult to meet, project planners may allow u_{MR} to be larger. In this case, project planners may choose σ_{MR} to be as large as $\Delta/3$ or any calculated value that allows the data quality objectives to be met at an acceptable effort. Two situations that may make this possible are if σ_S is believed to be less than $\Delta/10$ or if it is not difficult to make the additional measurements required by the larger overall data variance ($\sigma_M^2 + \sigma_S^2$).

Example 4: Suppose the uncertainty in Example 2 of u_{MR} = 800 Bq/m^2 cannot be achieved because of the variability in instrument efficiency with surface roughness. A required measurement method uncertainty, u_{MR}, as large as Δ / 3 ≈ 2,700 Bq/m^2 may be possible if σ_S is small or if more measurements are taken per survey unit.

5.5.2 Determine the Required Measurement Method Uncertainty at Concentrations Other Than the UBGR

The most important MQO for data evaluation is the one for measurement method uncertainty at a specified concentration. This MQO is expressed as the required measurement method uncertainty (u_{MR}) at the UBGR. However, to properly evaluate the data usability of measurement results at concentrations other than the UBGR, the implications of this requirement must be extended both above and below the UBGR.

When the concentration is less than or equal to the UBGR, the combined standard uncertainty, u_c, (CSU) of a measured result should not exceed the required measurement method uncertainty, u_{MR}, specified at the UBGR. When the concentration is greater than the UBGR, the relative combined standard uncertainty (RCSU), φ_{MR}, of a measured result should not exceed the required relative measurement method uncertainty at the UBGR. This is illustrated in Example 5 and Figure 5.1.

Example 5: Suppose the action level is 10,000 Bq/m^2 and the discrimination limit is 3,000. Scenario A is used, so the UBGR = AL = 10,000 Bq/m^2 and the LBGR = DL = 3,000 Bq/m^2. Thus the width of the gray region, Δ= 10,000 – 3,000 = 7,000. If decisions are to be made about individual items, α = 0.05, and β = 0.05, then the required measurement uncertainty at 10,000 Bq/m^2 is

$$u_{MR} = \frac{\Delta}{z_{1-\alpha} + z_{1-\beta}} = \frac{10{,}000 \text{ Bq/m}^2 \text{-} 3{,}000 \text{ Bq/m}^2}{z_{0.95} + z_{0.95}} = \frac{7{,}000 \text{ Bq/m}^2}{1.645 + 1.645} \approx 2{,}000 \text{ Bq/m}^2$$

The required measurement method uncertainty, u_{MR}, is 2,000 Bq/m^2 at 10,000 Bq/m^2. Thus, for any measured result less than 10,000 Bq/m^2, the reported combined standard uncertainty, u_c, should be less than or equal to 2,000 Bq/m^2. For example, a reported result of 4,500 Bq/m^2 with a CSU of 1,900 Bq/m^2 would meet the requirement. A reported result of 7,700 Bq/m^2 with a CSU 2,500 Bq/m^2 would not meet the requirement.

The required relative measurement method uncertainty (φ_{MR}) is 2,000 Bq/m^2 / 10,000 Bq/m^2 = 20% at 10,000 Bq/m^2. Thus, for any measured result greater than 10,000 Bq/m^2, the reported RCSU should be less than or equal to 20%. For example, a reported result of 14,500 Bq/m^2 with a CSU of 2,900 Bq/m^2 would meet the requirement because 2,900/14,500 = 20%. A reported result of 18,000 Bq/m^2 with a CSU 4,500 Bq/ cm^2 would not meet the requirement because 4,500/18,000 = 25%.

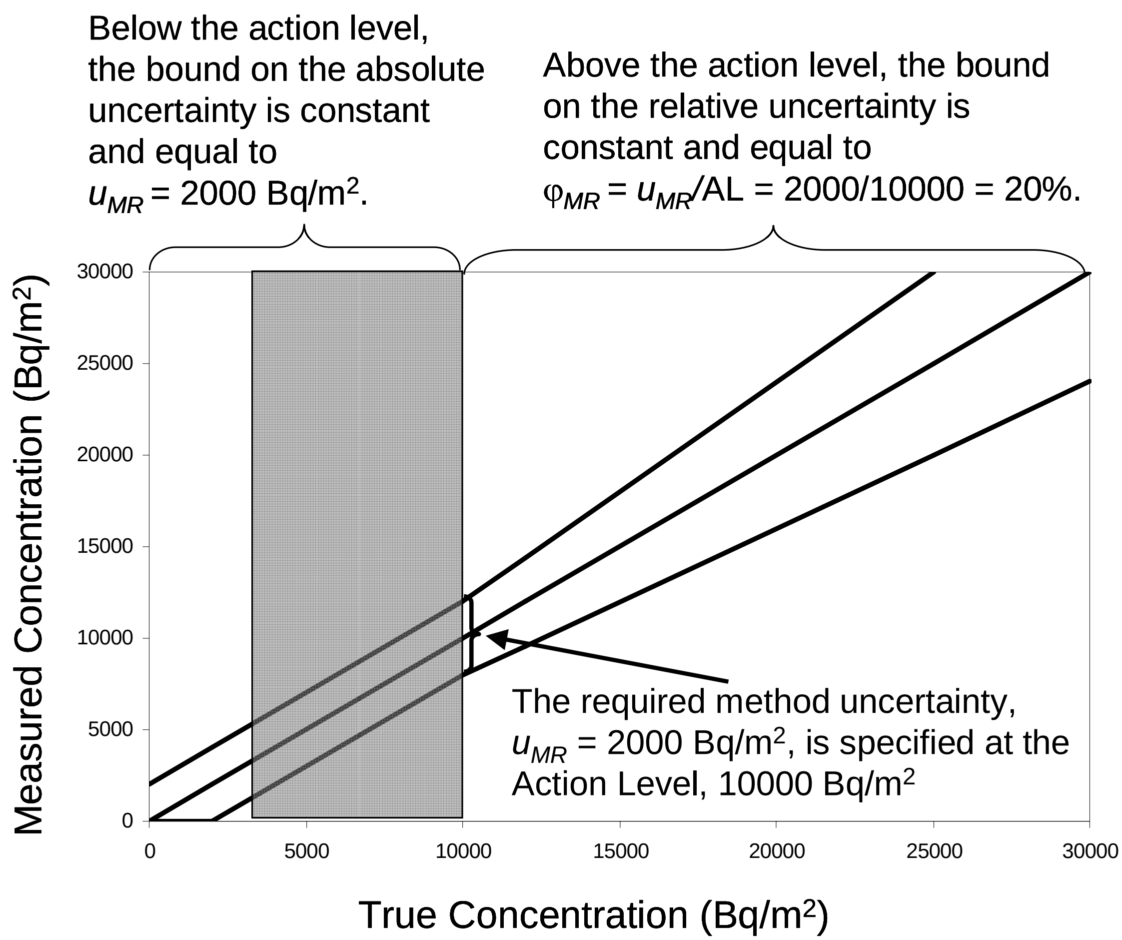

Figure 5.1 Example of the Required Measurement Uncertainty at Concentrations other than the UBGR. In this Example the UBGR Equals the Action Level. (see Example 5)

This check of measurement quality against the required measurement method uncertainty relies on having realistic estimates of the measurement uncertainty. Often reported measurement uncertainties are underestimated, particularly if they are confined to the estimated Poisson counting uncertainty (see Appendix G.2). Tables of results are sometimes presented with a column listing simply "±" without indicating how these numbers were obtained. Often it is found that they simply represent the square root of the number of counts obtained during the measurement. The method for calculating measurement uncertainty, approved by both the International Organization for Standardization (ISO) and the National Institute of Standards and Technology (NIST) is discussed in the next section.

5.6 Determine Measurement Uncertainty

This section discusses the evaluation and reporting of measurement uncertainty. Measurements always involve uncertainty, which must be considered when measurement results are used as part of a basis for making decisions. Every measured and reported result should be accompanied by an explicit uncertainty estimate. One purpose of this section is to give users of data an understanding of the causes of measurement uncertainty and of the meaning of uncertainty statements; another is to describe procedures that can be used to estimate uncertainties. Much of this material is derived from MARLAP Chapter 19.

In 1980, the Environmental Protection Agency published a report entitled "Upgrading Environmental Radiation Data," which was produced by an ad hoc committee of the Health Physics Society (EPA 1980). Two of the recommendations of this report were that:

1. Every reported measurement result (x) should include an estimate of its overall uncertainty (u_x) that is based on as nearly a complete an assessment as possible.

2. The uncertainty assessment should include every significant source of inaccuracy in the result.

The concept of traceability is also defined in terms of uncertainty. Traceability is defined as the "property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties" (ISO 1996). Thus, to realistically make the claim that a measurement result is "traceable" to a standard, there must be a chain of comparisons (each measurement having its own associated uncertainty) connecting the result of the measurement to that standard.

This section considers only measurement variability, σ_M. Reducing spatial variability, σ_S, by segregating M&E was discussed in Section 5.4. Spatial variability due to field sampling uncertainties is often larger than measurement uncertainties. Although this statement may be true in some cases, this is not an argument for failing to perform a full evaluation of the measurement uncertainty. A realistic estimate of the measurement uncertainty is one of the most useful data quality indicators for a result (see Section 3.8).

Although the need for reporting uncertainty has sometimes been recognized, often it consists of only the estimated component due to Poisson counting statistics. This is done because it is easier than a full uncertainty analysis, but it can be misleading because it is at best only a lower bound on the uncertainty and may lead to incorrect decisions based on overconfidence in the measurement. Software is available to perform the mathematical operations for uncertainty evaluation and propagation, eliminating much of the difficulty in implementing the mathematics of uncertainty calculations. There are several examples of such software (McCroan 2006, GUM Workbench 2006, Kragten 1994, and Vetter 2006).

5.6.1 Use Standard Terminology

The methods, terms, and symbols recommended by MARSAME for evaluating and expressing measurement uncertainty are described in the Guide to the Expression of Uncertainty in Measurement, abbreviated as GUM, which was published by ISO (ISO 1995). The ISO methodology is summarized in the NIST Technical Note TN-1297 (NIST 1994).

The result of a measurement is generally used to estimate some particular quantity called the measurand. The difference between the measured result and the actual value of the measurand is the error of the measurement. Both the measured result and the error may vary with each repetition of the measurement, while the value of the measurand (the true value) remains fixed. The error of a measurement is unknowable, because one cannot know the error without knowing the true value of the quantity being measured (the measurand). For this reason, the error is primarily a theoretical concept. However, the uncertainty of a measurement is a concept with practical uses. According to the GUM and NIST Technical Note 1297, the term "uncertainty of measurement" denotes the values that could reasonably be attributed to the measurand. In practice, there is seldom a need to refer to the error of a measurement, but an uncertainty should be stated for every measured result.

The first step in defining a measurement process is to define the measurand clearly. The specification of the measurand is always ambiguous to some extent, but it should be as clear as necessary for the intended purpose of the data. For example, when measuring the activity of a radionuclide on a surface, it is generally necessary to specify the activity, the date and time, what area of the surface was measured, and where.

Often the measurand is not measured directly but instead an estimate is calculated from the measured values of other input quantities, which have a known mathematical relationship to the measurand. For example, input quantities in a measurement of radioactivity may include the gross count, blank or background count, counting efficiency and area measured. The mathematical model measurement process specifies the relationship between the output quantity, Y, and measurable input quantities, $X_1, X_2, \ldots, X_N$, on which its value depends:

$$Y = f(X_1, X_2, \ldots, X_N) .$$

The mathematical model for a radioactivity measurement may have the simple form:

$$\text{Measurement} = \frac{\text{(Gross Instrument Signal) - (Blank Signal)}}{\text{Efficiency}}$$

Each of the quantities shown here may actually be a more complicated expression. For example, the efficiency may be the product of factors such as surveyor efficiency, surface roughness efficiency correction, and the instrument counting efficiency. Interferences may be due to ambient background or other radionuclides that have interactions with the detector in a manner that contributes spuriously to the gross instrument signal.

When a measurement is performed, a specific value x_i is estimated for each input quantity, X_i, and an estimated value, y, of the measurand is calculated using the relationship $y = f(x_1, x_2, \ldots, x_N)$. Since there is an uncertainty in each input estimate, x_i, there is also an uncertainty in the output estimate, y. Determining the uncertainty of the output estimate y requires that the uncertainties of all the input estimates x_i be determined and expressed in comparable forms. The uncertainty of x_i is expressed in the form of an estimated standard deviation, called the standard uncertainty and denoted by $u(x_i)$. The ratio $u(x_i) / |x_i|$ is called the relative standard uncertainty of x_i , where $|x_i|$ is the absolute value of x_i.

The partial derivatives, $\partial f / \partial x_i$, are called sensitivity coefficients, usually denoted c_i. The c_i measure how much f changes when x_i changes. The standard uncertainties are combined with sensitivity coefficients to obtain the component of the uncertainty in y due to x_i, $c_i u(x_i)$. The square of the combined standard uncertainty, denoted by $u_c^2(y)$, is called the combined variance. It is obtained using the formula for the propagation of uncertainty[1]:

$$u_c^2(y) = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i) = \sum_{i=1}^{N} c_i^2 u^2(x_i)$$

. The square root of the combined variance is the combined standard uncertainty of y, denoted by $u_c(y)$. Further details of this process are given in Appendix G.2.1.

5.6.2 Consider Sources of Uncertainty

The following sources of uncertainty should be considered:

- Radiation counting
- Instrument calibration (e.g., counting efficiency)
- Variable instrument backgrounds
- Variable counting efficiency (e.g., due to the instrument or to source geometry and placement)
- Interferences, such as crosstalk and spillover

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[1] If the input estimates are potentially correlated, covariance estimates $u(x_i,x_j)$ must also be determined. The covariance $u(x_i,x_j)$ is often recorded and presented in the form of an estimated correlation coefficient, $r(x_i,x_j)$, which is defined as the quotient $u(x_i,x_j) / u(x_i)u(x_j)$. See Appendix G.2.

Other sources of uncertainty could include:

- Temperature and pressure
- Volume and mass measurements
- Determination of counting time and correction for dead time
- Time measurements used in decay and ingrowth calculations
- Approximation errors in simplified mathematical models
- Published values for half-lives and radiation emission probabilities

There are a number of sources of measurement uncertainty in gamma-ray spectroscopy, including:

- Poisson counting uncertainty;
- Compton baseline determination;
- Background peak subtraction;
- Multiplets and interference corrections;
- Peak-fitting model errors;
- Efficiency calibration model error;
- Summing;
- Density-correction factors; and
- Dead time.

Additional discussion of some major sources of uncertainty may be found in Appendix G.2.2.

Example 6: Consider a simple measurement of a sample. The activity will be calculated from

$$y = \frac{(N_S / t_S) - (N_B / t_B)}{\varepsilon}$$

Where:

y is the sample activity (Bq),

ε is the counting efficiency 0.4176 (s^{-1}/Bq),

N_S is the gross count observed during the measurement of the source, (11578).

t_S is the source count time (300 s),

N_B is the observed background count (87),

t_B is the background count time (6,000 s),

The combined standard uncertainty of ε is given by $u_c(\varepsilon) = 0.005802$. This is shown in Example 2 in Appendix G.2.2.2. Assume the radionuclide is long-lived; so, no decay corrections are needed. The uncertainties of the count times are also assumed to be negligible. The standard uncertainties in N_S and N_B will be estimated as $\sqrt{N_S}$ and $\sqrt{N_B}$ using the Poisson assumption.

Then $y = \dfrac{(N_S / t_S) - (N_B / t_B)}{\varepsilon} = \dfrac{(11578/300) - (87/6000)}{0.4179} = 92.316$

$$u_c^2(y) = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i) = \sum_{i=1}^{N} c_i^2 u^2(x_i)$$

$$= \left(\frac{\partial \frac{(N_S/t_S) - (N_B/t_B)}{\varepsilon}}{\partial N_S} \right)^2 u^2(N_S) + \left(\frac{\partial \frac{(N_S/t_S) - (N_B/t_B)}{\varepsilon}}{\partial N_B} \right)^2 u^2(N_B) + \left(\frac{\partial \frac{(N_S/t_S) - (N_B/t_B)}{\varepsilon}}{\partial \varepsilon} \right)^2$$

$$= \left(\frac{1/t_S}{\varepsilon} \right)^2 u^2(N_S) + \left(\frac{-1/t_B}{\varepsilon} \right)^2 + u^2(N_B) \left(\frac{-(N_S/t_S) - (N_B/t_B)}{\varepsilon^2} \right)^2 u^2(\varepsilon)$$

$$= \left(\frac{1/300}{0.4176} \right)^2 \sqrt{11578}^2 + \left(\frac{-1/6000}{0.4176} \right)^2 + \sqrt{87}^2 \left(\frac{-(11578/300) - (87/6000)}{0.4176^2} \right)^2 0.005802^2$$

=0.7379 + 0.00001+ 1.6384 = 2.3851. Note that these calculations show which input quantities are contributing the most to the combined variance. N_S contributes 0.7379/2.3851 ~ 31%. N_B contributes virtually nothing. The uncertainty in the efficiency contributes 1.6384/2.3851 ~ 69%. An analysis such as this is called an uncertainty budget, and quickly points out where improvements in the measurement may be made.

Taking the square root of the combined variance we find $u_c(y)$ = 1.54439. Usually the combined standard uncertainty is rounded to two significant figures and the result is rounded to match the same number of decimal places. So the result would be reported as 92.3 Bq with a combined standard uncertainty of 1.5 Bq.

Note that if the uncertainty in the efficiency had been neglected, the combined standard uncertainty would have been underestimated as 0.86 Bq, and would have been attributed entirely to the uncertainty in the sample counts. This illustrates the importance of including all significant sources of uncertainty in the calculations. Many of these calculations can be done using computer software programs mentioned earlier.

A much more detailed and involved example is given in Appendix G.2.3

5.6.3 Summary of Uncertainty Calculation and Reporting

- Use the terminology and methods of the Guide to the Expression of Uncertainty in Measurement (ISO 1995) for evaluating and reporting measurement uncertainty.
- Follow QC procedures that ensure the measurement process remains in a state of statistical control, which is a prerequisite for uncertainty evaluation.
- Account for possible blunders or other spurious errors. Spurious errors indicate a loss of statistical control of the process and are not part of the uncertainty analysis described above.
- Report each measured value with either its combined standard uncertainty (or its expanded uncertainty, see Appendix G.2.1.7).
- Reported measurement uncertainties should be clearly explained. (In particular, when an expanded uncertainty is reported, the coverage factor should be stated and the basis for the coverage probability should also be given, see Appendix G.2.1.7).
- Consider all possible sources of measurement uncertainty and evaluate and propagate the uncertainties from all sources believed to be potentially significant in the final result.
- Each uncertainty should be rounded to either one or two significant figures, and the measured value should be rounded to the same number of decimal places as its uncertainty.
- Results should be reported as obtained together with their uncertainties (whether positive, negative, or zero).

5.7 Determine Measurement Detectability

This section is a summary of issues related to measurement detection capabilities. Much of this material is derived from the MARLAP Chapter 20. More detail may be found in Appendix G.3.

Environmental radioactivity measurements may involve material with very small amounts of the radionuclide of interest. Measurement uncertainty often makes it difficult to distinguish such small amounts from zero. Therefore, an important MQO of a measurement process is its detection capability, which is usually expressed as the smallest concentration of radioactivity that can be reliably distinguished from zero. Effective project planning requires knowledge of the detection capabilities of the measurement method that will be or could be used. This section explains a MQO called the minimum detectable concentration (MDC) and describes radioactivity detection capabilities, as well as methods for calculating it.

The method most often used to make a detection decision about radiation or radioactivity involves the principles of statistical hypothesis testing. It is a specific example of a Scenario B hypothesis testing procedure described in Section 4.2.4. To "detect" the radiation or radioactivity requires a decision on the basis of the measurement data that the radioactivity is present. The detection decision involves a choice between the null hypothesis (H_0): There is no radiation or radioactivity present (above background), and the alternative hypothesis (H_1): There is radiation or radioactivity present (above background). In this context, a Type I error is to conclude that radiation or radioactivity is present when it actually is not, and a Type II error is to conclude that radiation or radioactivity is not present when it actually is.[2] Making the choice between these hypotheses requires the calculation of a critical value. If the measurement result exceeds this critical value, the null hypothesis is rejected and the decision is that radiation or radioactivity is present.

[2] Note that in any given situation only one of the two types of decision error is possible. If the sample *does not* contain radioactivity, a Type I error is possible. If the sample *does* contain radioactivity, a Type II error is possible.

5.7.1 Calculate the Critical Value

The critical value defines a region where the net instrument signal (count) is too large to be compatible with the premise that there is no radioactivity present. It has become standard practice to make the detection decision by comparing the net instrument count to its critical value, S_C. The net count is calculated from the gross count by subtracting the estimated background and any interferences.[3]

The mean value of the net instrument count typically is positive when there is radioactivity present (i.e., above background). The gross count must be corrected by subtracting an estimate of the count produced under background conditions. See section G.2.2 (Instrument Background).

Table 5.1 lists some formulas that are commonly used to calculate the critical value, S_C, together with the major assumptions made in deriving them. Note specifically that the Stapleton formulas given in rows 3-5 are especially appropriate when the total background is less than 100 counts.

These formulas depend on N_B (the background count), t_B (the background count time), t_S (the sample count time), and $z_{1-\alpha}$ (the $(1-\alpha)$-quantile of the standard normal distribution). The value of α determines the sensitivity of the test. It is the probability that a detection decision is made when no radioactivity above background is actually present.

More detail on the calculation of critical values is given in Appendix G.3.3. Software (Strom 1999) is available for calculating S_C using the equations recommended here, among others.

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[3] The presence of other radiation or radioactivity that hinder the ability to analyze for the radiation or radioactivity of interest.

Table 5.1 Recommended Approaches for Calculating the Critical Net Signal, S_C[4]

	Critical Value Equation	Assumptions	Background Count
1	$S_C = z_{1-\alpha}\sqrt{N_B \frac{t_S}{t_B}\left(1+\frac{t_S}{t_B}\right)}$	Poisson	> 100
2	$S_C = 2.33\sqrt{N_B}$	Poisson $\alpha = 0.05$ $t_B = t_S$	> 100
3	$S_C = d\times\left(\frac{t_S}{t_B}-1\right)+\frac{z_{1-\alpha}^2}{4}\times\left(1+\frac{t_S}{t_B}\right)+z_{1-\alpha}\sqrt{\left(N_B+d\right)\frac{t_S}{t_B}\left(1+\frac{t_S}{t_B}\right)}$	Stapleton $t_B \neq t_S$	< 100
4	$S_C = 0.4\times\left(\frac{t_S}{t_B}-1\right)+\frac{1.645^2}{4}\times\left(1+\frac{t_S}{t_B}\right)+1.645\sqrt{\left(N_B+0.4\right)\frac{t_S}{t_B}\left(1+\frac{t_S}{t_B}\right)}$	Stapleton $t_B \neq t_S$ $\alpha = 0.05$ $d = 0.4$	< 100
5	$S_C = 1.35+2.33\sqrt{N_B+0.4}$	Stapleton $t_B = t_S$ $\alpha = 0.05$ $d = 0.4$	< 100

[4] These expressions for the critical net count depends for its validity on the assumption of Poisson counting statistics. If the variance of the blank signal is affected by interferences, or background instability, then the Equation 20.7 of MARLAP may be more appropriate.

Example 7: A 600-second background measurement is performed on a proportional counter and 108 beta counts are observed. A sample is to be counted for 300 s. Estimate the critical value of the net count when $\alpha = 0.05$.

$$S_C = z_{1-\alpha}\sqrt{N_B \frac{t_S}{t_B}\left(1+\frac{t_S}{t_B}\right)}$$

$$S_C = 1.645\sqrt{108\times\left(\frac{300\text{ s}}{600\text{ s}}\right)\left(1+\frac{300\text{ s}}{600\text{ s}}\right)} = 14.8\text{ net counts}$$

Therefore, if 15 or more net counts are observed, the decision will be made that the sample contains radioactivity above background. Values of S_C should be rounded up when necessary to make sure that the specified Type I error probability, α, is not exceeded.

5.7.2 Calculate the Minimum Detectable Value of the Net Count

Table 5.2 lists some formulas that are commonly used to calculate the minimum detectable net count, S_D, together with the major assumptions made in deriving them. S_D, is defined as the mean value of the net count that gives a specified probability, $1-\beta$, of yielding an observed count greater than its critical value S_C. Therefore S_C must be calculated before S_D. Note specifically that the Stapleton formulas given in rows 4 and 5 are especially appropriate when the total background is less than 100 counts. Generally, the Stapleton methods may be used for both high and low total background counts as they agree well with the more traditional methods when the background counts are over 100. The simpler more familiar formulas have been included for completeness.

It is important that the assumptions used to calculate S_D are consistent with those that were used to calculate S_C. The equations for S_D depend on the same variables as S_C, namely N_B, t_B, and t_S. Notice that neither α nor $z_{1-\alpha}$ appears explicitly, rather they enter the calculation through S_C. However, β now enters the calculation of S_D through $z_{1-\beta}$. The value of β, like α, is usually chosen to be 0.05 or is assumed to be 0.05 by default if no value is specified.

Table 5.2 Recommended Approaches for Calculating the Minimum Detectable Net Count.[5]

	Minimum Detectable Net Signal Equation	Assumptions	Background Count
1	$S_D = S_C + \frac{z_{1-\beta}^2}{2} + z_{1-\beta}\sqrt{\frac{z_{1-\beta}^2}{4} + S_C + N_B\frac{t_S}{t_B}\left(1+\frac{t_S}{t_B}\right)}$	Poisson $t_B \neq t_S$	> 100
2	$S_D = z_{1-\beta}^2 + 2S_C$	Poisson $t_B \neq t_S$ $\alpha = \beta$	> 100
3	$S_D = 2.71 + 2S_C = 2.71 + 2(2.33\sqrt{N_B}) = 2.71 + 4.66\sqrt{N_B}$	Poisson $\alpha = \beta = 0.05$ $t_B = t_S$	> 100
4	$S_D = \frac{(z_{1-\alpha}+z_{1-\beta})^2}{4}\left(1+\frac{t_S}{t_B}\right) + (z_{1-\alpha}+z_{1-\beta})\sqrt{N_B\frac{t_S}{t_B}\left(1+\frac{t_S}{t_B}\right)}$	Stapleton	< 100
5	$S_D = 5.41 + 4.65\sqrt{N_B}$	Stapleton $\alpha = \beta = 0.05$ $t_B = t_S$	< 100

[5] These expressions for the critical value net count depend for their validity on the assumption of Poisson counting statistics. If the variance of the blank signal is affected by interferences, or background instability, then Equation 20.7 of MARLAP may be more appropriate.

Example 8 A 600-second background measurement on a proportional counter produces 108 beta counts and a source is to be counted for 300 s. Assume the background measurement gives the available estimate of the true mean background count rate and use the value 0.05 for Type I and Type II error probabilities. From section 5.7.5, Example 7, the critical net count, S_C, equals 14.8, so $S_D = z_{1-\beta}^2 + 2S_C = 1.645^2 + 2\,(14.8) = 32.3$ net counts. Values of S_D should be rounded up when necessary to make sure that the specified Type II error probability, β, is not exceeded.

The relationship between the critical value of the net count, S_C, and the minimum detectable net count, S_D, is shown in Figure 5.2. The net counts obtained for a blank sample will usually be distributed around zero as shown. Occasionally, a net count rate above S_C may be obtained by chance. The probability that this happens is controlled by the value of α, shown as the lightly shaded area in Figure 5.2. Smaller values of α result in larger values of S_C and vice versa. The minimum detectable value of the net count S_D is that value of the mean net count that results in a detection decision with probability $1 - \beta$. That is, there is only a β, shown as the more darkly shaded area in Figure 5.2, of yielding an observed count less than S_C. Smaller values of β result in larger values of S_D and vice versa.

More information detail on the calculation of the minimum detectable value of the net instrument signal, S_D, is given in Appendix G.3.4.

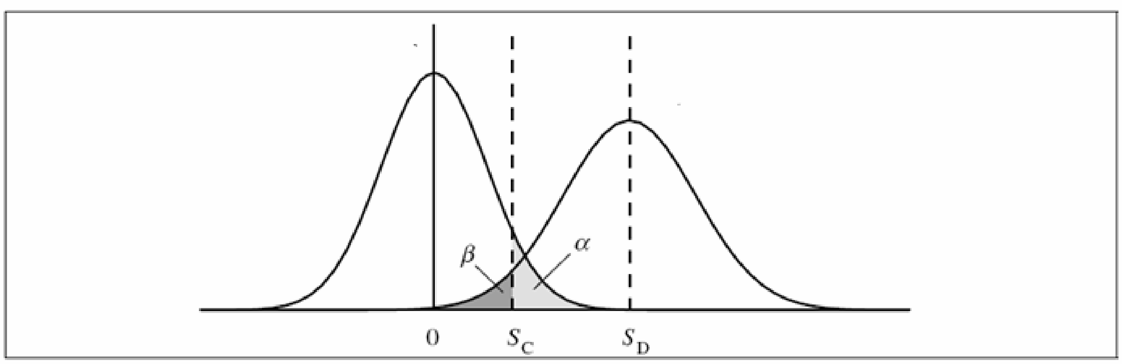

Figure 5.2 The critical net signal (S_C) and the minimum detectable net signal (S_D). (Adapted from Figure 20.1 of MARLAP)

5.7.3 Calculate the MDC

The MDC is usually obtained from the minimum detectable value of the net instrument count, S_D. The MDC is by definition an estimate of the true concentration of the radiation or radioactivity required to give a specified high probability that the measured response will be greater than the critical value. The common practice of comparing a measured concentration to the MDC, instead of to the S_C, to make a detection decision is incorrect.

To calculate the MDC, the minimum detectable value of the net count, S_D, must first be converted to the detectable value of the net count rate, S_D/ t_S (s^{-1}). This in turn must be divided by the counting efficiency, ε $(s^{-1})/(\mathrm{Bq})$ to get the minimum detectable activity, y_D. Finally, the minimum detectable activity can be divided by the sample volume or mass to obtain the MDC. At each stage in this process, additional uncertainty may be introduced by the uncertainties in time, efficiency, volume, mass, etc. Thus prudently conservative values of these factors should be used so that the desired detection power, $1 - \beta$, at the MDC is maintained. Another approach would be to recognize that y_D itself has an uncertainty which can be calculated using the methods of Section 5.6. Thus any input quantity that is used to convert from S_D to y_D that has significant uncertainty can be incorporated to asses the overall uncertainty in the MDC. Additional discussion of the calculation of the MDCs is given in Appendix G.3.5.

Example 9: Continuing example 8, $S_D = 32.3$ net counts.

Assuming negligible uncertainty in the count time, the net count rate is

$S_D/ t_S = 32.3/300 = 0.1077$ (s^{-1}).

The mean efficiency from Example 6 in Section 5.6.3 was 0.4176 $(s^{-1})/(\mathrm{Bq})$ with a combined standard uncertainty of $u_c(\varepsilon) = 0.005802$.

In Example 8 the value 0.05 was specified for both Type I and Type II error probabilities. So the specified power was $1 - \beta = 1 - 0.05 = 0.95$.

Assume a normal distribution for ε, to obtain a 95% probability of detection for the MDC.

To account for the variability in the efficiency, the value used for ε should be the 5th percentile, i.e., 0.4176 – 1.645(0.005805) = 0.4081.

Thus the minimum detectable activity, $y_D = \dfrac{S_D / t_s}{\varepsilon} = 0.1077 / 0.4081 = 0.2639$ Bq.

Using the mean value of the efficiency would potentially underestimate the minimum detectable activity as $y_D = \frac{S_D / t_s}{\varepsilon} = 0.1077 / 0.4176 = 0.2578\,\text{Bq}$.

These values for y_D would then be divided by the mass or volume of the sample to yield the MDC.

5.7.4 Summary of Measurement Detectability

The concepts surrounding the MDC and the critical value are illustrated in Figure 5.3, using familiar formulae for S_C and S_D discussed above, assuming a background count of $N_B = 100$ with $\alpha = \beta = 0.5$. In this case, the equation in row 2 of Table 5.1 was used to obtain $S_C = 23.3$, and the corresponding equation in row 3 of Table 5.2 to obtain $S_D = 49.3$. The use of these equations implies $\alpha = \beta = 0.05$ and $t_B = t_S$.

Note, the upper abscissa scale is in concentration and the lower abscissa scale is in net count. These are related by the efficiency at the point where the MDC corresponds to the minimum detectable net count, S_D. Each of the curves illustrates the distribution of mean net counts (or concentration) that may exist for a measurement. The width of these curves represents the variation due to counting statistics. The variability due to other factors is associated with uncertainty in ε. Changes in the relationship between the lower and the upper scales result from changes in ε. This illustrates the importance of choosing realistic, or even conservative, values of ε. Note that the probability of making a detection decision (which is proportional to the area of each curve to the right of S_C) depends on the concentration, increasing from 5% at background to 95% at the MDC, passing through 50% at S_C. This is perhaps more clearly shown in Figure 5.4, which plots the probability of making a detection decision as a function of net count (or concentration).

Figure 5.4 shows that for concentrations corresponding to net counts between 0 and S_C the probability of a non-detect is greater than 50%. For concentrations corresponding to net counts between S_C and S_D the probability of detection is greater than 50%, but less than 95%. Concentrations above the MDC (with net counts greater than S_D) are highly likely to be detected, but will have relative standard uncertainties that are somewhat large.

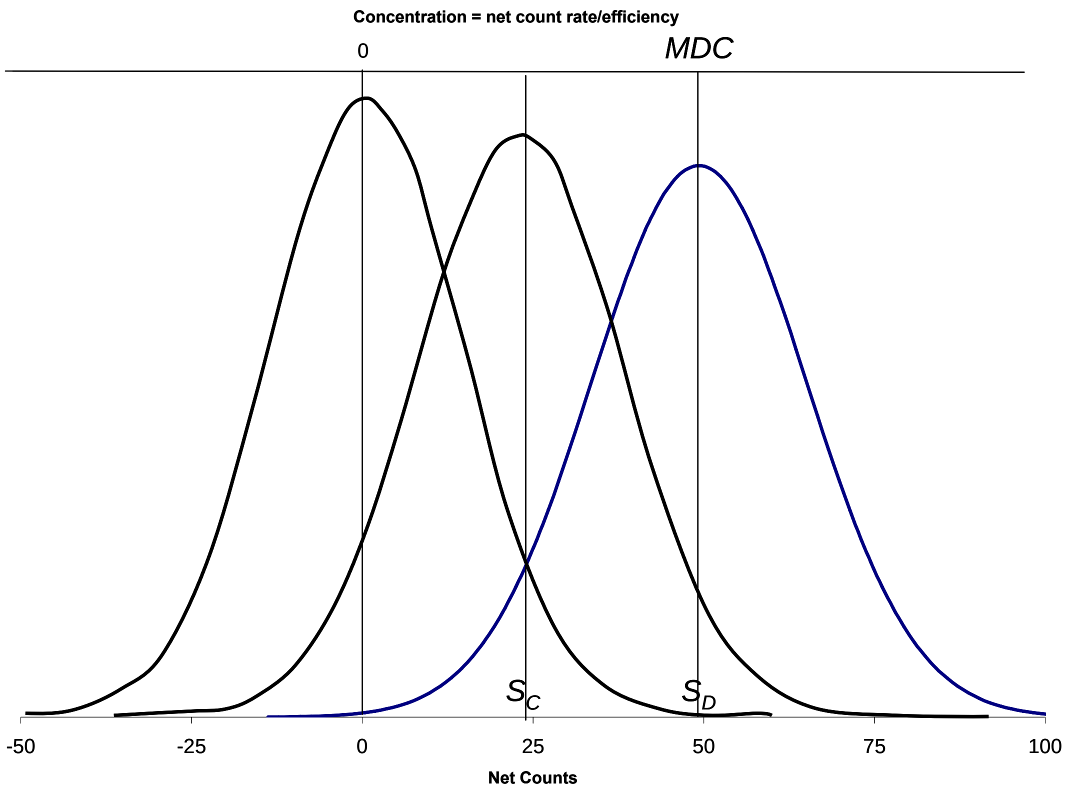

Figure 5.3 Relationship Between the Critical Value, the Minimum Detectable Net Counts and the MDC (upper x-axis in units of concentration, lower x-axis in units of net counts)

5.7.5 Measurement Detectability Recommendations

- When a detection decision is required, it generally should be made by comparing the net count to its corresponding critical value.
- Expressions for the critical value and minimum detectable value should be chosen that are appropriate for the structure and statistics of the measurement process.
- An appropriate background should be used to predict the count produced when there is no radioactivity present in the sample.
- The minimum detectable value (MDC) should be used only as a MQO for the measurement method. To make a detection decision, a measurement result should be compared the critical value and never to the MDC.

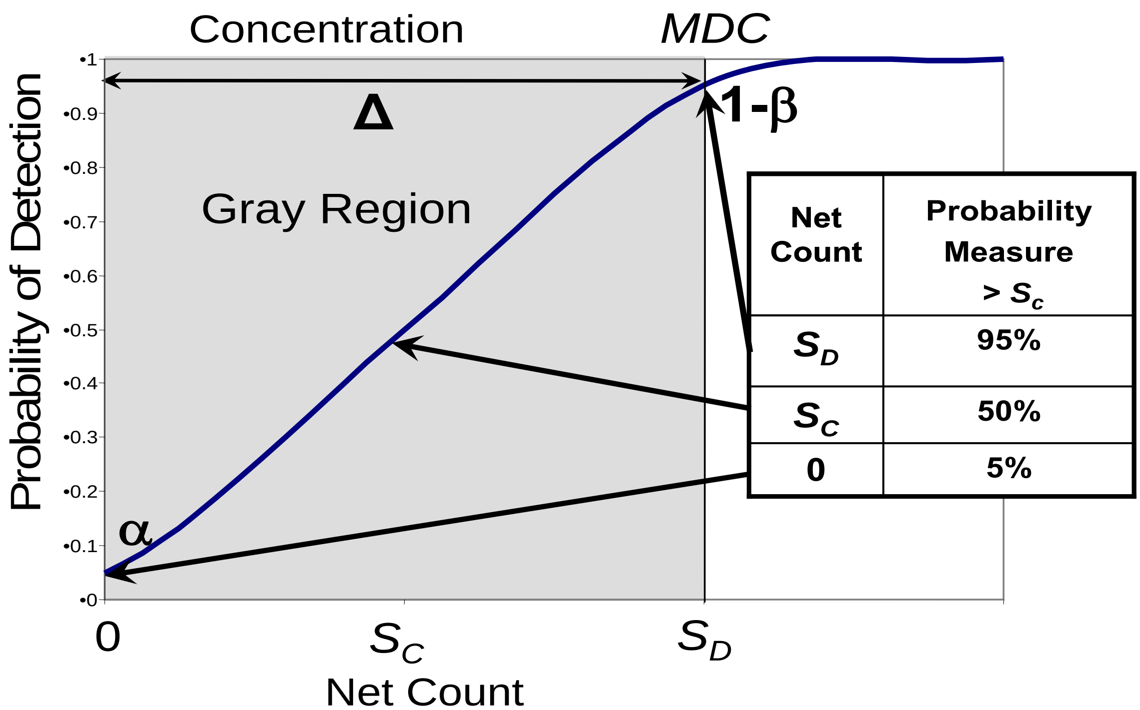

Figure 5.4 Probability of Detection as a Function of Net Count (lower x-axis) and Concentration (upper x-axis)

- The validity of the Poisson approximation for the measurement process should be confirmed using the methods described in MARLAP Chapter 20 before using an expression for the critical value that is based on Poisson statistics. When the Poisson approximation is inappropriate for determining the critical value, estimating σ by the sample standard deviation of replicated background measurements is preferable to using the square root of the number of counts.

- Consider all significant sources of variance in the instrument signal (or other response variable) when calculating the critical value, S_C, and minimum detectable value, S_D.

- Report each measurement result and its uncertainty as obtained even if the result is less than zero. Never report a result as “less than MDC” or “less than S_C.”

- The MDC should not be used for projects where the issue is a quantitative comparison of the average of several measurements to a limit rather than just a detection decision made for a single measurement. For these projects, the minimum quantifiable concentration is a more relevant MQO for the measurement process (see Section 5.8).

5.8 Determine Measurement Quantifiability

This section discusses issues related to measurement quantifiability. Much of this material is derived from the MARLAP Chapter 20.

Action levels are frequently stated in terms of a quantity or concentration of radioactivity, rather than in terms of detection. In these cases, project planners may need to know the quantification capability of a measurement method, or its capability for precise measurement. The quantification capability is expressed as the smallest concentration of radiation or radioactivity that can be measured with a specified relative standard deviation. This section explains an MQO called the minimum quantifiable concentration (MQC), which may be used to describe quantification capabilities.

The MQC of the concentration, y_Q, is defined as the concentration at which the measurement process gives results with a specified relative standard deviation $1 / k_Q$ where k_Q is usually chosen to be 10 for comparability.

Historically much attention has been given to the detection capabilities of radiation and radioactivity measurement processes, but less attention has been given to quantification capabilities. For some projects, quantification capability may be a more relevant issue. For example, suppose the purpose of a project is to determine whether the ^{226}Ra concentration on material at a site is below an action level. Since ^{226}Ra can be found in almost any type of naturally occurring material, it may be assumed to be present in every sample, making detection decisions unnecessary. The MDC of the measurement process obviously should be less than the action level, but a more important question is whether the MQC is less than the action level.

A common practice in the past has been to select a measurement method based on the minimum detectable concentration (MDC), which is defined in Section 5.7. For example, the Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM 2002) says:

> During survey design, it is generally considered good practice to select a measurement system with an MDC between 10-50% of the DCGL [action level].

Such guidance implicitly recognizes that for cases when the decision to be made concerns the mean of a population that is represented by multiple measurements, criteria based on the MDC may not be sufficient and a somewhat more stringent requirement is needed. The requirement that the MDC (approximately 3-5 times σ_M) be 10% to 50% of the action level is tantamount to requiring that σ_M be 0.02 to 0.17 times the action level – in other words, the relative standard deviation should be approximately 10% at the action level. However, the concentration at which the relative standard deviation is 10% is the MQC when k_Q assumes its conventional value of 10. Thus, a requirement that is often stated in terms of the MDC may be more naturally expressed in terms of the MQC, e.g. by saying that the MQC should not exceed the action level.

5.8.1 Calculate the MQC

The minimum quantifiable concentration, when there are no interferences can be calculated from:

$$y_Q = \frac{k_Q^2}{2t_S\varepsilon(1-k_Q^2\phi_{\hat{\varepsilon}}^2)}\left(1+\sqrt{1+\frac{4(1-k_Q^2\phi_{\hat{\varepsilon}}^2)}{k_Q^2}\left(N_B\frac{t_S}{t_B}\left(1+\frac{t_S}{t_B}\right)\right)}\right)$$

Where:

t_S is the count time for the source, s,

t_B is the count time for the background, s,

N_B is the background count,

$\phi_{\hat{\varepsilon}}^2$ is the relative variance of the measured efficiency, $\hat{\varepsilon}$. (See for example Appendix G.2.2.2)

k_Q assumes its conventional value of 10

Example 10: Continuing example 9, $t_S = 300$, $t_B = 600$, $N_B = 108$, $\phi_{\hat{\varepsilon}}^2 = (0.005805/0.4176)^2 = 0.0001932$, and $k_Q = 10$. So,

$$y_Q = \frac{k_Q^2}{2t_S\varepsilon(1-k_Q^2\phi_{\hat{\varepsilon}}^2)}\left(1+\sqrt{1+\frac{4(1-k_Q^2\phi_{\hat{\varepsilon}}^2)}{k_Q^2}\left(N_B\frac{t_S}{t_B}\left(1+\frac{t_S}{t_B}\right)\right)}\right)$$

$$= \frac{100}{2(300)(0.4176)(1-100(0.0001932))}\left(1+\sqrt{1+\frac{4(1-100(0.0001932))}{100}\left(108\frac{300}{600}\left(1+\frac{300}{600}\right)\right)}\right)$$

= 1.239 Bq. This value for y_Q would then be divided by the mass or volume of the sample to yield the MQC.

The next example is given to verify that the equation for y_Q does indeed produce a value with a relative uncertainty of 10%. It also provides an opportunity to give another illustration of the methodology for the calculation of measurement uncertainty developed in Section 5.6. Additional information on the calculation of MQCs is given in Appendix G.4.

Example 11: The calculations of Example 10 can be verified by calculating the uncertainty of a measurement made at the MQC. The expected number of counts for a sample at the MQC counted for 300 s:

$$N_S = y_Q t_S \varepsilon + N_B (t_S / t_B) = (1.239\text{ Bq})(300\text{ s})(0.4176) + (108\text{ s}^{-1})(300/600) = 209,$$

rounded to the nearest whole number.

The model equation is the same as was used in Example 6, Section 5.6.3:

$y = \dfrac{(N_S / t_S) - (N_B / t_B)}{\varepsilon}$, so the equation for the combined standard uncertainty is the same:

$$u_c^2(y) = \left(\frac{1/t_S}{\varepsilon}\right)^2 u^2(N_S) + \left(\frac{-1/t_B}{\varepsilon}\right)^2 + u^2(N_B)\left(\frac{-(N_S/t_S)-(N_B/t_B)}{\varepsilon^2}\right)^2 u^2(\varepsilon)$$

$$= \left(\frac{1/300}{0.4176}\right)^2 (209) + \left(\frac{-1/600}{0.4176}\right)^2 (108) + \left(\frac{-(209/300)-(108/600)}{0.4176^2}\right)^2 (0.005805)^2$$

$$= 1.332\times10^{-2} + 1.72\times10^{-3} + 8.5\times10^{-4} = 1.589\times10^{-2}$$

$u_c(y) = \sqrt{1.59\times10^{-2}} = 0.126$. Thus the relative uncertainty at the MQC is 0.126/1.239 = 0.1017. This means, apart from some small difference due to rounding, the relative measurement uncertainty at y_Q is 10%, as should be the case for the MQC.

5.8.2 Summary of Measurement Quantifiability

Figure 5.5 is a modification of Figure 5.4, illustrating the relationships between the critical value, the MDC, the MQC and the probability of exceeding the critical value. As can be seen, the issue of detection is almost moot at the MQC. The probability of detection is near 100%. However, the MQC specifies a concentration with a defined relative standard uncertainty, making comparisons between measurements or comparisons between measurements and regulatory criteria meaningful.

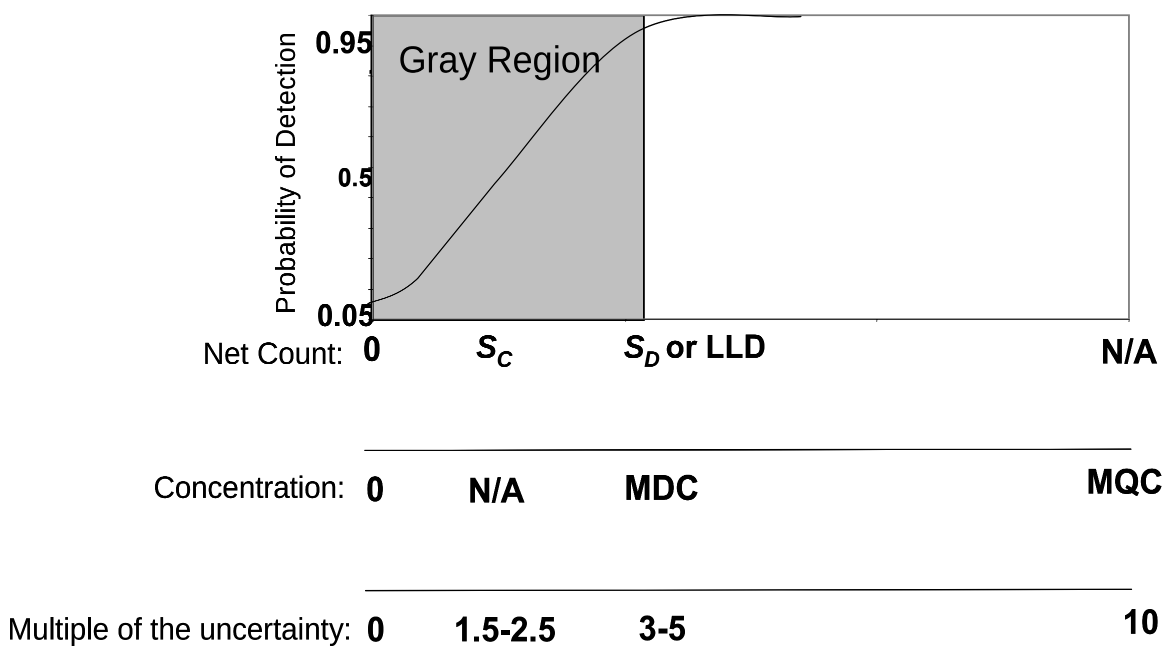

Figure 5.5 Relationships Among the Critical Value, the MDC, the MQC and the Probability of Exceeding the Critical Value

Three x-axis scales are shown in Figure 5.5, for net count, concentration, and multiple of measurement uncertainty. This emphasizes, for example, that the minimum detectable net count, S_D, corresponds to the minimum detectable concentration (MDC), but has different units. It also shows that the minimum quantifiable concentration (MQC) is by definition 10 times the measurement uncertainty at that concentration. The critical value of the net count, S_C, has no corresponding common term in concentration units. This is because detection decisions are usually made on the basis of the net counts (instrument reading). These are inherently qualitative "yes or no" decisions. The relationship between S_C and S_D and the multiple of the uncertainty varies according to which set of assumptions are used and which equations in Table 5.2 and Table 5.3 are appropriate to those assumptions. Therefore an approximate range is shown for these quantities on the multiple of uncertainty axis.

5.9 Select a Measurement Technique and Instrumentation Combination

The combination of a measurement technique with instrumentation is used to select a measurement method to implement a disposition survey design based on the ability to meet the MQOs (see Section 3.3.2 and 5.5). A realistic determination of the measurement method uncertainty (see Section 5.6) is critical to demonstrating a method meets the MQOs. Other considerations when selecting a measurement method include:

- Health and safety concerns (Section 5.2),
- M&E handling issues (Section 5.3),
- Segregation (Section 5.4),
- Measurement detectability (Section 5.7), and
- Measurement quantifiability (Section 5.8).

The measurement techniques discussed in Section 5.9.1 can all be classified as scanning measurements (constant motion involved in the surveying procedure) or fixed measurements (surveying discrete locations without motion). Fixed measurements consist of in situ measurements (the detection instrument moves to the M&E or measures the M&E in its entirety), and sampling (removing part of the M&E for separate analysis).

Instrumentation for performing radiological measurements is varied and constantly being improved. The discussions in Section 5.9.2 provide an overview of some commonly used types of instruments and how they might be applied to disposition surveys. The purpose of the discussions on instrumentation is not to provide an exhaustive list of acceptable instruments, but to provide examples of how instrumentation and measurement techniques can be combined to meet the survey objectives. Additional information on instrumentation is found in Appendix D.

Section 5.9.3 provides information on selecting a combination of instrumentation and survey technique to provide a measurement method. It is necessary that the selected measurement method meet the MQOs established during survey design (see Section 3.8). Selection of instrumentation can be an iterative process. The appropriate MQO (e.g., MDC, MQC) may not be attainable with some measurement methods. In some cases selection of a different instrument may be all that is necessary, while in other cases a different measurement technique or an entirely different measurement method will need to be considered.

5.9.1 Measurement Techniques

A measurement technique describes how a measurement is performed. The detector can be moved relative to the M&E (i.e., scanning), used to perform static measurements of the M&E in place (i.e., in situ or direct measurements), or some representative portion of the M&E can be removed for analysis in a different location (i.e., sampling).

5.9.1.1 Scanning Techniques

Scanning techniques generally consist of moving portable radiation detectors at a specified distance above the physical surface of a survey unit at some specified speed to meet the MQOs. Alternatively, the M&E can be moved past a stationary instrument at a specified distance and speed (e.g., conveyorized systems or certain portal monitors). Scanning techniques can be used alone to demonstrate compliance with a disposition criterion (i.e., scan-only surveys, Section 4.4.1), or combined with sampling in a MARSSIM-type survey design (see Section 4.4.3). Scanning is used in MARSSIM-type surveys to locate radiation anomalies by searching for variations in readings, indicating gross radioactivity levels that may require further investigation or action. Scanning techniques can more readily provide thorough coverage of a given survey unit and are often relatively quick and inexpensive to perform. Scanning often represents the simplest and most practical approach for performing MARSAME disposition surveys.

Maintaining the specified distance and speed during scanning can be difficult, especially with hand-held instruments and irregularly shaped M&E. Variations in source-to-detector distance and scan speed can result in increased total measurement method uncertainty. Determining a calibration function for situations other than surficial radionuclides uniformly distributed on a plane can be complicated, and may also contribute to the total measurement method uncertainty.

5.9.1.2 In Situ Measurements

In situ measurements are taken by placing the instrument in a fixed position at a specified distance[6] from the surface of a given survey unit of M&E and taking a discrete measurement for a pre-determined time interval. Single in situ measurements can be performed on individual objects or groups of M&E. Multiple in situ measurements can be combined to provide several different views of the same object, or used to provide measurements for a specified fraction of the M&E. In situ measurements can also be performed at random or systematic locations, combined with scanning measurements, in a MARSSIM-type survey design. In situ measurements are generally used to provide an estimate of the average radionuclide concentration or level of radioactivity over a certain area or volume defined by the calibration function.

Determining a calibration function for situations other than radionuclides uniformly distributed on a plane or through a regularly shaped volume (e.g., a disk or cylinder) can be complicated, and may contribute to the total measurement method uncertainty. In situ techniques are not typically used to identify small areas or volumes of elevated radionuclide concentration or activity.

5.9.1.3 Sampling

Sampling consists of removing a portion of the M&E for separate analysis. This measurement technique surpasses the detection capabilities of measurement techniques that may be implemented with the M&E left in place, enabling the analysis of complicated radioisotope mixtures, difficult-to-measure radionuclides, and extremely low concentrations of residual radioactivity. Sampling is used to provide an estimate of the average radionuclide concentration or level of radioactivity for a specified area or volume. The sample locations may be located using a random or systematic grid, depending on the objectives of the survey. Sampling is

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[6] Measurements at several distances may be needed. Near-surface or surface measurements provide the best indication of the size of the area of elevated radionuclide concentrations or radioactivity, and are useful for model implementation. Gamma measurements at one meter provide a good estimate of potential direct external exposure (MARSSIM 2002).

typically combined with scanning in a MARSSIM-type survey design, where sampling is used to evaluate the average concentration or activity and scanning is used to identify small areas or volumes with elevated radionuclide concentrations or radioactivity. Sampling may also be used to validate data collected using other measurement techniques.

Sampling (combined with laboratory analysis) typically requires the most time for data generation of all the surveying techniques discussed in this chapter and is often the most expensive. Sampling is not an effective technique for identifying small areas or volumes of elevated radionuclide concentrations or levels of radioactivity.

5.9.2 Select Instrumentation

This section briefly describes the typical types of instrumentation that may be used to conduct MARSAME disposition surveys. More detailed information relevant to each type of instrument and measurement method is provided in Appendix D.

5.9.2.1 Hand-Held Instruments

Hand-held instruments are typically composed of a detection probe (utilizing a single detector) and an electronic instrument to provide power to the detector and to interpret data from the detector to provide a measurement display. They may be used to perform scanning surveys or in situ measurements. Hand-held measurements also allow the user the flexibility to constantly vary the source-to-detector geometry for obtaining data from difficult-to-measure areas.

5.9.2.2 Volumetric Counters (Drum, Box, Barrel, 4π Counters)

Box counting systems typically consist of a counting chamber, an array of detectors configured to provide 4π counting geometry, and microprocessor-controlled electronics that allow programming of system parameters and data-logging. Volumetric counters are used to perform in situ measurements on entire pieces of small M&E.

5.9.2.3 Conveyorized Survey Monitoring Systems

Conveyorized survey monitoring systems automate the routine scanning of M&E. Conveyorized survey monitoring systems typically perform scanning surveys by moving M&E through a detector array on a conveyor belt. Conveyorized survey monitoring systems may be utilized to take in situ measurements by halting the conveyor and continuing the measurement to improve the detection efficiency.

5.9.2.4 In Situ Gamma Spectroscopy

Some in situ gamma spectroscopy (ISGS) systems consist of a small hand-held unit that incorporates the detector and counting electronics into a single package. Other ISGS systems consist of a semiconductor detector, a cryostat, a multi-channel analyzer (MCA) electronics package that provides amplification and analysis of the energy pulse heights, and a computer system for data collection and analysis. ISGS systems are typically applied to perform in situ measurements, but they may be incorporated into innovative detection equipment set-ups to perform scanning surveys.

5.9.2.5 Portal Monitors

Portal monitors utilize a fixed detector array through which M&E are passed to typically perform scanning surveys (objects may also remain stationary within the detector array to perform in situ measurements). Portal monitors are typically used to perform scanning surveys of vehicles.[7] In situ measurements may be utilized with portal monitors by taking motionless measurements to improve the detection efficiency.

5.9.2.6 Laboratory Analysis

Laboratory analysis consists of analyzing a portion or sample of the M&E. The laboratory will generally have recommendations or requirements concerning the amount and types of samples that can be analyzed for radionuclides or radiations. Communications should be established between the field team collecting the samples and the laboratory analyzing the samples. More information on sampling is provided in Section 5.9.1.3. Laboratory analyses can be developed for any radionuclide with any material, given sufficient resources. Laboratory analyses typically require more time to complete than field analyses. The laboratory may be located onsite or

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[7] Specialized vehicle monitors are available that monitor rates of change in ambient background to account for differences in vehicles being scanned to improve measurement detectability.

offsite. The quality of laboratory data is typically greater than data collected in the field because the laboratory is better able to control sources of measurement method uncertainty. The planning team should consider the resources available for laboratory analysis (e.g., time, money), the sample collection requirements or recommendations, and the requirements for data quality (e.g., MDC, MQC) during discussions with the laboratory.

5.9.3 Select a Measurement Method

Table 5.3 and Table 5.4 illustrate the potential applications and associated size restrictions for combinations of the instrument and measurement techniques discussed in Sections 5.9.1 and 5.9.2, respectively. Sampling followed by laboratory analysis is not included in these tables, but is considered "GOOD" for all applications. Please note the following qualifiers:

GOOD	The measurement technique is well-suited for performing this application
FAIR	The measurement technique can adequately perform this application
POOR	The measurement technique is poorly-suited for performing this application
NA	The measurement technique cannot perform this application

Table 5.3 illustrates that most measurement techniques can be applied to almost any M&E and type of radioactivity. The quantity of M&E to be surveyed becomes a major factor for the selection of measurement instruments and techniques described in this chapter. Hand-held measurements and techniques are generally the most efficient technique for surveying small quantities of M&E.

Table 5.3 Potential Applications for Instrumentation and Measurement Technique Combinations

Radiation Type	Hand-Held Instruments	Volumetric Counters	Portal Monitors	In Situ Gamma Spectroscopy	Conveyorized Survey Monitoring Systems
In Situ Measurements					
Alpha	FAIR	FAIR	POOR	NA	FAIR
Beta	GOOD	FAIR	FAIR	NA	GOOD
Photon	GOOD	GOOD	GOOD	GOOD	GOOD
Neutron	GOOD	FAIR	GOOD	NA	GOOD
Scanning Surveys					
Alpha	POOR	NA	POOR	NA	POOR
Beta	GOOD	NA	FAIR	NA	FAIR
Photon	GOOD	NA	GOOD	GOOD	GOOD
Neutron	FAIR	NA	FAIR	NA	FAIR

Table 5.4 Survey Unit Size and Quantity Restrictions for Instrumentation and Measurement Technique Combinations

Size of Items	Number of Survey Units or Items	Hand-Held Instruments	Volumetric Counters	Portal Monitors	In Situ Gamma Spectroscopy	Conveyorized Survey Monitoring Systems
In Situ Measurements						
> 10 m^3	Few	GOOD	NA	FAIR	GOOD	POOR
	Many	POOR	NA	FAIR	GOOD	POOR
1 to 10 m^3	Few	GOOD	FAIR	FAIR	GOOD	FAIR
	Many	POOR	FAIR	FAIR	GOOD	FAIR
< 1 m^3	Few	GOOD	GOOD	POOR	GOOD	GOOD
	Many	FAIR	GOOD	POOR	GOOD	GOOD
Scanning Surveys						
> 10 m^3	Few	GOOD	NA	GOOD	FAIR	POOR
	Many	FAIR	NA	GOOD	FAIR	POOR
1 to 10 m^3	Few	GOOD	NA	FAIR	FAIR	FAIR
	Many	FAIR	NA	FAIR	FAIR	FAIR
< 1 m^3	Few	GOOD	NA	POOR	FAIR	GOOD
	Many	GOOD	NA	POOR	FAIR	GOOD

Facilities that conduct routine surveys on substantial quantities of specific types of M&E may benefit financially from investing in measurement instruments and techniques that require less manual labor to conduct disposition surveys. For example, it will require significantly more time for a health physics technician to survey a toolbox of tools and equipment used in a radiologically-controlled area using hand-held surveying techniques and instruments than the time to complete the surveying using a box counting system. Use of such automated systems will also reduce the potential for ergonomic injuries, and attendant costs, associated with routine, repetitive surveys performed using hand-held instruments. Hand-held surveying remains the more economical choice for a small quantity of tools and toolboxes, but as the quantity of tools and toolboxes increases, the cost of a box counting system becomes an increasingly worthwhile investment to reduce manual labor costs associated with surveying. Note that some M&E have no survey design options that are described as "GOOD" in these two tables (e.g., a large quantity of M&E impacted with residual alpha radioactivity with survey unit sizes greater than 10 m^3). The planning team should revisit earlier DQO selections to see if a different approach is more acceptable (e.g., review selection of disposition options in Section 2.4). Each type of measurement technique has associated advantages and disadvantages, some of which are summarized in Table 5.5. All the measurement techniques described in this table include source-to-detector geometry and spatial variability as common disadvantages.

5.10 Quality Control

The purpose of QC is to ensure that measurement and other data-producing systems operate within defined performance limits as specified in planning. QC programs can lower the chances of making an incorrect decision and help the decision maker understand the level of uncertainty that surrounds the decision. QC operations help identify where errors are occurring, what the magnitude of that error is, and how that error might impact the decision-making process.

This section discusses QC in the context of implementation. Information is provided on measurement performance indicators as well as instrument performance indicators. Evaluation of QC data is discussed in Section 6.2.2.1.

1001 **Table 5.5 Advantages and Disadvantages of Instrumentation and Measurement Technique**
1002 **Combinations**

Instrument	Measurement Technique	Advantages	Disadvantages
Hand-Held Instruments	In Situ	• Generally allows flexibility in media to be measured • Detection equipment is usually portable • Detectors are available to efficiently measure alpha, beta, gamma, x-ray, and neutron radiation • Generally acceptable for performing measurements in difficult-to-measure areas • Measurement equipment is relatively low cost • May provide a good option for small quantities of M&E	• Requires a relatively large amount of manual labor as a surveying technique; may make surveying large quantities of M&E labor-intensive • Detector windows may be fragile • Most do not provide nuclide identification
Hand-Held Instruments	Scanning	• Generally allows flexibility in media to be measured • Detection equipment is usually portable • Detectors are available to efficiently measure beta, gamma, x-ray, and neutron radiation • Generally good for performing measurements in difficult-to-measure areas • Measurement equipment is relatively low cost • May provide a good option for small quantities of M&E	• Requires a relatively large amount of manual labor as a surveying technique; may make surveying large quantities of M&E labor-intensive • Detector windows may be fragile • Most do not provide nuclide identification • Incorporates more potential sources of uncertainty than most instrument and measurement technique combinations • Potential ergonomic injuries and attendant costs associated with repetitive surveys.

Table 5.5 Advantages and Disadvantages of Instrumentation and Measurement Technique Combinations (continued)

Instrument	Measurement Technique	Advantages	Disadvantages
Volumetric Counters	Sampling	• Able to measure small items • Designs are available to efficiently measure gamma, x-ray, and alpha radiation • Requires relatively small amount of labor • May be cost-effective for measuring large quantities of M&E	• May not be suited for measuring radioactivity in difficult-to-measure areas • Size of instrumentation may discourage portability
Portal Monitors	In situ	• Able to measure large objects • Designs are available to efficiently measure gamma, x-ray, and neutron radiation • Requires relatively small amount of labor • May be cost-effective for measuring large quantities of M&E	• Not ideal for measuring alpha or beta radioactivity • May not be ideal for measuring radioactivity in difficult-to-measure areas • Size of detection equipment may discourage portability
Portal Monitors	Scanning	• Able to measure large objects • Efficient designs available for gammas, X-rays, and neutron radiation • Residence times are generally short • May not require objects to remain stationary during counting • Requires relatively small amount of labor • May be cost-effective for measuring large quantities of M&E	• Not ideal for measuring alpha or beta radioactivity • Source geometry is an important consideration • May not be ideal for measuring radioactivity in difficult-to-measure areas • Size of detection equipment may discourage portability
In Situ Gamma Spectroscopy (ISGS)	In situ	• Provides quantitative measurements with flexible calibration • Generally requires a moderate amount of labor • May be cost-effective for measuring large quantities of M&E	• Instrumentation may be expensive and difficult to set up and maintain • May require liquid nitrogen supply (with ISGS semiconductor systems) • Size of detection equipment may discourage portability

1005 **Table 5.5 Advantages and Disadvantages of Instrumentation and Measurement Technique**
1006 **Combinations (continued)**

Instrument	Measurement Technique	Advantages	Disadvantages
In Situ Gamma Spectroscopy (ISGS)	Scanning	• Provides quantitative measurements with flexible calibration • Generally requires a moderate amount of labor • May be cost-effective for measuring large quantities of M&E	• Instrumentation may be expensive and difficult to set up and maintain • May require liquid nitrogen supply (with ISGS semiconductor systems) • Size of detection equipment may discourage portability
Conveyorized Survey Monitoring Systems	In situ	• Requires relatively small amount of labor after initial set up • May be cost-effective for measuring large quantities of M&E	• Instrumentation may be expensive and difficult to set up and maintain • May not be ideal for assessing radioactivity in difficult-to-measure areas • Size of detection equipment may discourage portability • Typically does not provide nuclide identification
Conveyorized Survey Monitoring Systems	Scanning	• Requires relatively small amount of labor after initial set up • May be cost-effective for measuring large quantities of M&E	• Instrumentation may be expensive and difficult to set up and maintain • May not be ideal for assessing radioactivity in difficult-to-measure areas • Size of detection equipment may discourage portability • Typically does not provide nuclide identification

Table 5.5 Advantages and Disadvantages of Instrumentation and Measurement Technique Combinations (continued)

Instrument	Measurement Technique	Advantages	Disadvantages
Laboratory Analysis	Sampling	• Generally provides the lowest MDCs and MQCs, even for difficult-to-measure radionuclides • Allows positive identification of radionuclides without gammas	• Most costly and time-consuming measurement technique • May incur increased overhead costs while personnel are waiting for analytical results • Great care must be taken to ensure samples are representative • Detector windows may be fragile

5.10.1 Measurement Performance Indicators

Measurement performance indicators are used to evaluate the performance of the measurement method. These indicators describe how the measurement method is performing to ensure the survey results are of sufficient quality to meet the survey objectives.

5.10.1.1 Blanks

Blanks are measurements of materials with little or no radioactivity and none of the radionuclide(s) of concern present. Blanks are performed to determine whether the measurement process introduces any increase in count rate that could impact the measurement method detection capability. Blanks should be representative of all measurements performed using a specific method (i.e., combination of instrumentation and measurement technique). When practical, the blank should consist of the same or equivalent material(s) as the M&E being surveyed.

Blanks are typically performed before and after a series of measurements to demonstrate the measurement method was performing adequately throughout the survey. At a minimum, blanks should be performed at the beginning and end of each shift. When large quantities of data are collected (e.g., scanning measurements) or there is an increased potential for radionuclide contamination of the instrument (e.g., removable or airborne radionuclides), blanks may be performed more frequently. In general, a blank should be collected whenever enough measurements have been performed such that it is not practical to repeat those measurements if a problem is identified.

A sudden change in a blank result indicates a condition requiring immediate attention. Sudden changes are caused by the introduction of a radionuclide, a change in ambient background, or instrument instability. Gradual changes in blank values indicate a need to inspect all survey areas for sources of radionuclides or radioactivity. Gradual build up of removable radionuclides over time or instrument drift and deterioration can result in slowly increasing blank values. High variability in blank values can result from instrument instability or improper classification (i.e., high activity and low activity M&E combined into a single survey unit. It is important to correct any problems with blanks to ensure measurement detectability (see Section 5.7) is not compromised.

5.10.1.2 Replicate Measurements

Replicate measurements are two or more measurements performed on the same M&E. Replicates are performed primarily to provide an estimate of precision for the measurement method. The reproducibility of measurement results should be evaluated by replicates to establish this component of measurement uncertainty (see Section 5.6).

Replicates are typically performed at specified intervals during a survey (e.g., 5% of all measurements or once per day). Replicates should be used to evaluate each batch of data used to support a disposition decision (e.g., one replicate per survey unit). For single measurement surveys or scan-only surveys where decisions are made based on every measurement, typically 5% of all measurements are replicated.

Precision exhibits a range of values and depends in part on the material being measured and the activity level. Small changes in precision are expected, and the acceptable range of variability should be established prior to initiating data collection activities. The main causes for lack of precision include problems with repeating measurements on irregularly shaped M&E, the material being measured, counting statistics when the activity levels are low, and instrument contamination.

5.10.1.3 Spikes, Standards, and Certified Reference Materials

Spikes, standards, and certified reference materials are materials with known composition and known radionuclide content. Materials with known radionuclide concentrations are used to evaluate bias in the measurement method. It is unlikely that certified reference materials will be available for most field applications.

Measurements of materials with known radionuclide concentrations are typically performed at specified intervals during a survey (e.g., 5% of all measurements or once per day). At a minimum, these measurements should be used to evaluate each batch of data used to support a disposition decision (i.e., at least one spike or standard per survey unit).

M&E cover a broad range of physical forms and materials that can change a measurement method's expected bias. Tracking results of measurements with known activity can provide an indication of the magnitude of bias. However, M&E can be very complex and subject to large variability, so care should be taken in interpreting these results. The activity level associated with the standards should be considered. In general, activity levels close to the action levels (or discrimination limits) will provide adequate information on the performance of the measurement system.

5.10.2 Instrument Performance Indicators

Instrument performance indicators provide information on how an instrument is performing. Evaluation of these indicators provides information on the operation of the instruments.

5.10.2.1 Performance Tests

Performance tests should be performed periodically and after maintenance to ensure that the instruments continue to meet performance requirements for measurements. An example of a performance test is a test for response time. Performance requirements should be met as specified in the applicable sections of ANSI N323A (ANSI 1997), ANSI N42.17A 9ANSI 2003b), and ANSI N42.17C (ANSI 1989). These tests may be conducted as part of the calibration procedure.

5.10.2.2 Functional Tests

Functional tests should be performed prior to initial use of an instrument. These functional tests should include:

- General condition
- Battery condition
- Verification of current calibration (i.e., check to see that the date due for calibration has not passed)
- Source and background response checks (and other tests as applicable to the instrument)
- Constancy check

The effects of environmental conditions (temperature, humidity, etc.) and interfering radiation on an instrument should be established prior to use. The performance of functional tests should be appropriately documented. This may be as simple as a checklist on a survey sheet, or may include more detailed statistical evaluation such as a chi-square test.

5.10.2.3 Instrument Background

All radiation detection instruments have a background response, even in the absence of a sample or radiation source (see Section 3.4.2). Inappropriate background correction will result in measurement error and increase the uncertainty of data interpretation.

5.10.2.4 Efficiency Calibrations

Detector efficiency is critical for converting the instrument response to activity (MARSAME Section 6.4, MARSSIM Section 6.5.4, MARLAP Chapter 16). Routine performance checks may be used to demonstrate the system's operational parameters are within acceptable limits, and these measurements are typically included in the assessment of bias. The system's operational parameters may be tracked using control charts.

5.10.2.5 Energy Calibrations (Spectrometry Systems)

Spectrometry systems identify radionuclides based on the energy of the detected radiations. A correct energy calibration is critical to accurately identify radionuclides. An incorrect energy calibration may result in misidentification of peaks, or failure to identify radionuclides present in the M&E being investigated.

5.10.2.6 Peak Resolution and Tailing (Spectrometry Systems)

The shape of the full energy peak is important for identifying radionuclides and quantifying their activity with spectrometry systems. Poor peak resolution and peak tailing may result in larger measurement uncertainty, or in failure to identify the presence of peaks based on shape. Consistent problems with peak resolution indicate the presence of an analytical bias.

5.10.2.7 Voltage Plateaus (Gas Proportional Systems)

The accuracy of results using a gas proportional system can be affected if the system is not operated with its detector high voltage adjusted such that it is on a stable portion of the operating plateau.

5.10.2.8 Self Absorption, Backscatter, and Crosstalk

Alpha and beta measurement results can be affected by the M&E through self-absorption and backscatter. Measurement systems simultaneously detecting alpha and beta particles using an electronic discriminator (e.g., gas flow proportional detectors) can be affected by crosstalk (i.e., identification of alpha particles as beta particles and vice versa). Accurate differentiation between alpha and beta activity depends on the assessment and maintenance of information on self-absorption and crosstalk.

5.11 Report the Results

Once the instruments have been checked to ensure proper operation, the data should be collected in a manner consistent with the survey design. Any field changes and deviations from survey design should be documented and described in sufficient detail to enable an independent re-creation and evaluation at some future time.

The reported measurements should comprise raw data that includes background radioactivity (i.e., gross measurement data). Electronic instruments with data logging capabilities should be used when applicable. Electronic data should be exported and backed up periodically to minimize the chance of losing data and the need for re-surveying.

Use of a measurement identification system should be considered. If required by the objectives of the survey, the identification system should be developed and used such that each measurement is assigned and labeled with a unique (preferably sequential) identifying number, the collection date and time, the measurement location, and any applicable comments.

While MARSAME does not make specific recommendations with regard to approved media formats for storing documentation, some users of MARSAME (e.g., private industry nuclear power plants) may be required to retain documentation in media formats prescribed by State and Federal rules of evidence. Similarly, State and Federal rules of evidence may specify retention periods for documentation that exceed internal facility requirements. Compliance with State and Federal rules of evidence is intrinsic to maintaining legally defensible records for insurance and litigation-related purposes.

Documentation of the survey measurements should provide a complete and unambiguous record of the data collected. Documentation should also include descriptions of variability and other conditions pertaining to the M&E that may have affected the measurement capabilities of the survey procedure, and photographs where applicable. The documentation itself should be clear, legible, retained, retrievable, and to the level of detail required..

Negative results (net activity below zero) can be obtained when an instrument background is subtracted from the measurement of a low activity sample. In the case where the activity is close to zero, the measurement uncertainty will result in a distribution of results where approximately one half are less than zero and one half are greater than zero. As long as the magnitude of negative values is comparable to the estimated measurement uncertainties and there is no discernible negative bias, negative results should be accepted as legitimate estimates of radionuclide concentrations or levels of radioactivity associated with the M&E. A preponderance of negative results, even if they are close to zero may indicate a bias or systematic error.

The inclusion of the information described above is important in creating comprehensive documentation to make disposition surveys technically and legally defensible. The collection of all necessary data prepares the MARSAME user to assess the results of the disposition survey, which is discussed in Chapter 6.